

Progress Report NAG 5-11623:

Propagation of Interplanetary Disturbances in the Outer Heliosphere

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Summary of Work

1. Publications:

- 1) There are total 20 papers have been published or accepted for publication in peer-reviewed journals
- 2) 6 papers have been published in J. Geophys. Res., 4 in Geophys. Res. Lett., 4 in Astrophys. J., 3 in Adv. Space Res., and 3 in other journals.

2. Main research work completed:

- 1) Finished a 1D and 2.5 D multi-fluid solar wind model.
- 2) Determined the solar wind slowdown and interstellar neutral density.
- 3) Tracked and studied the propagation of ICME from the inner to outer heliosphere.
- 4) Studied shock propagation and evolution in the outer heliosphere
- 5) Investigated statistical properties of the solar wind in the outer heliosphere.
- 6) Studied radial heliospheric magnetic field events.

Work completed

1. 1D and 2.5 D multi-fluid solar wind model

We have developed a one-dimensional, spherically symmetric, multi-fluid MHD model that includes solar wind protons and electrons, pickup ions, and interstellar neutral hydrogen. This model advances the existing solar wind models for the outer heliosphere in two important ways: one is that it distinguishes solar wind protons from pickup ions, and the other is that it allows for energy transfer from pickup ions to the solar wind protons. Model results compare favorably with the Voyager 2 observations.

Our 1-D multi-fluid MHD model in the outer heliosphere has been proved to be relatively accurate and useful in interpreting solar wind observations in the other heliosphere, however a full understanding of the propagation and evolution of the interplanetary disturbances requires 2-D and 3-D model. We have extended our one-dimensional, spherically symmetric, MHD model to 2.5D, which includes three components of the solar wind velocity and magnetic field. This model advances the existing 1D solar wind models for the outer heliosphere by allowing us to include the heliospheric current sheet and slow solar wind region, which is necessary to understand the solar wind at solar minimum.

2. Solar wind slowdown and interstellar neutral density

The solar wind in the outer heliosphere is fundamentally different from that in the inner heliosphere since the effects of interstellar neutrals become significant. The magnitude of the solar wind speed decrease from the inner to the outer heliosphere provides important information about the interaction of the heliosphere with the local interstellar medium (LISM), leading to better estimates of the size and shape of the heliosphere and of the LISM density. Using our newly developed model, we take advantage of the observations from multiple spacecraft (ACE, Ulysses and Voyager 2) in 1999 near solar maximum to examine the solar wind slowdown. We find a decrease in speed of 53-62 km/s at Voyager 2 (~60 AU) with respect to ACE and Ulysses measurements, or a 12-14% slowdown, the largest yet reported. The interstellar neutral hydrogen density is estimated to be 0.09 cm^{-3} at the termination shock, which is consistent with the estimations from other investigations.

3. ICME propagation from the inner to outer heliosphere

Large coronal mass ejections (CMEs) have major effects on the structure of the solar wind and the heliosphere. The plasma and magnetic field can be compressed ahead of interplanetary CMEs

(ICMEs) to form merged interaction regions (MIRs). Some ICMEs have an enhanced alpha abundance; this signature can be used to track these ICMEs through the heliosphere. We use the enhanced alpha signature and the multi-fluid model to track a CME on 23 September of 1998 from an active region on the Sun to Wind (1 AU), then

to Ulysses (5.3AU) and finally to Voyager 2 (58 AU). The arrival times of the CME ejecta at the three spacecraft are identified primarily by the increased alpha abundance. The observed plasma profiles and timing are close to those predicted by propagating the ICMEs outward (from Earth to Ulysses and from Ulysses to Voyager 2) using the multi-fluid model; thus the model results give us confidence that we observe the same event at all three spacecraft.

4. Shock propagation and evolution in the outer heliosphere

During the current solar cycle (Cycle 23), several major CMEs associated with solar flares produced large transient shocks which were observed by widely-separated spacecraft such as Wind at Earth and Voyager 2 beyond 60 AU. Using data from these spacecraft, we use the multi-fluid model to investigate shock propagation and interaction in the heliosphere. Specifically, we studied the Bastille Day 2000, April 2001 and Halloween 2003 events. A strong shock at Earth undergoes a dramatic change while propagating outward. For example, the Bastille Day 2000 CME shock had a speed jump of over 400 km/s at Earth and was detected by Voyager about 6 months later at 63 AU with a speed jump of only 65 km/s. However, a strong shock at Voyager 2

does not necessarily correspond to a strong shock at Earth. On October 16, 2001, Voyager 2 at 65 AU observed a strong shock with a speed jump over 100 km/s, the strongest shock recorded since 1991, but no single solar event was directly responsible for this shock. Instead, a series of solar events in April 2001 was responsible. The model results show that successive merging and interaction of relatively small interplanetary shocks could form a well-developed strong forward shock beyond 30 AU.

5. Statistical properties of the solar wind in the outer heliosphere

In a collaboration with L.F. Burlaga of GSFC, it is shown that the basic statistical properties of the solar wind in the outer heliosphere can be well produced by our model.

We studied the large-scale heliospheric magnetic field strength fluctuations as a function of distance from the Sun during the declining phase of a solar cycle, using our numerical model with observations made at 1 AU during 1995 as input. The model predicts that the magnetic field is quasi-periodic, that the amplitudes of fluctuations in B relative to the yearly averages are relatively large between 5 and 20 AU ("the corotating merged interaction region zone"), and that the fluctuations are aperiodic and their amplitudes are relatively small between 30 and 95 AU (the "wave interaction zone"). It predicts a transition between these two zones at ~ 25 AU. These results are consistent with a conceptual model proposed by Burlaga for the declining phase of the solar cycle. We also studied correlated solar wind speed, density, and magnetic field changes at Voyager 2, large-scale magnetic field fluctuations and development of the 1999-2000 GMIR, etc.

6. Radial heliospheric magnetic field events

The heliospheric magnetic field (HMF) direction, on average, conforms well to the Parker spiral. However, numerous examples of events where the HMF is oriented in near-radial directions for many hours have been reported on the basis of observations inside 5 AU from spacecraft such

ISEE-3 and Ulysses. We searched magnetic field data observed by Voyager 2 for all instances of radial fields with duration of 6 hours or more. Radial fields of significant duration at large distances are unusual as the Parker spiral is very tightly wound. The radial HMF events in the inner heliosphere typically occur at times when the solar wind speed is declining gradually, while they tend to be associated with steady solar wind speeds at distances beyond ~6 AU. The duration of these events appear to be independent of distance and solar cycle, with an average duration of ~11 hours. We find that a low-speed trough of limited duration in the solar wind speed near the Sun can produce the radial field events observed by Voyager 2.

Publications

1. Wang C., J.D. Richardson, Dynamic processes in the outer heliosphere: Voyager observations and models, in press, *Adv. Sp. Res.*, 2004.
2. Richardson J.D., Y. Liu, C. Wang, L.F. Burlaga, ICMEs at very large distances, in press, *Adv. Sp. Res.*, 2004.
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